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INTERACTION STUDIES OF LASER BEAMS
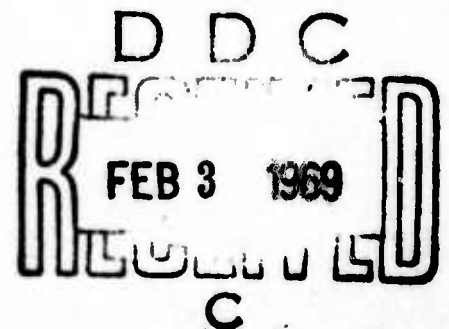## INTERSECTING IN AN ACTIVE MEDIUM
(Crossed Beam Laser)

Fifth

Semi-Annual Technical Summary Report

1 February 1968 – 31 July 1968

ONR Contract No. Nonr-5034(00)
Project Code No. 4730
ARPA Order No. 306

Prepared for

Office of Naval Research
Department of Navy
Washington 25, D. C.

Prepared by

Research and Development Center
General Electric Company
Schenectady, N. Y. 12301

S-69-1001

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(CROSSED BEAM LASER)

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Program Manager

Dr. J.C. Almasi

Principal Contributor:

D.K. Duston

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Submitted by

Heavy Military Electronics Systems
General Electric Company
Syracuse, New York

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Section I

SUMMARY

Because of excessive scattering of the Q-switched perturbing laser beam, the interaction amplifier experiments using the high power perturbing laser did not provide meaningful results. The excessive scattering was eliminated by a) using a sheet polarizer, b) employing a second, narrower entrance slit to the spectrometer, and c) rearranging the angular geometry of the probe and perturbing laser beams.

An abnormally low gain observed when conducting experiments at liquid nitrogen temperature was due to a small amount of frost depositing on the cooled ends of the interaction amplifier rod. This problem was eliminated by using dry nitrogen gas from a cylinder.

The net gain of the 15-cm long interaction amplifier rod was found to increase by 18% when cooled from 300°K to 77°K. The small increase should not significantly affect the accuracy of the gain measurements as a function of temperature.

In attempting to interpret the gain measurements of the interaction amplifier, it became evident that the gain would be influenced by both energy transfer across the fluorescence linewidth as well as the lifetime of the terminal level of the laser transition. By employing a Q-switched perturbing laser with a wide spectral output, energy transfer effects can be neglected. The terminal level lifetime can be measured by observing the recovery in gain after passage of the perturbing pulse.

If the terminal level lifetime is comparable to the duration of the perturbing pulse, it is possible to deduce the lifetime from the size and shape of the perturbing pulse emerging from the interaction amplifier relative to the input. The rate equations for a 4-level laser amplifier and the differential equation for a pulse traveling in a laser amplifier were analyzed. These coupled

differential equations can be solved using a computer by considering a) finite increments of time during the perturbing pulse, and b) finite increments of length along the interaction amplifier rod. A matrix formulation is required to calculate the pulse response as a function of terminal level lifetime. A comparison of the measured response (gain) with the theoretical will enable the determination of the lifetime.

Preliminary measurements of the terminal level lifetime indicates a value in the range between 20 and 50 nanoseconds for AOLux Type 1838 2% Nd-doped NS series glass.

Section II

WORK PERFORMED

A. INTERACTION AMPLIFIER EXPERIMENT

1. Reduction of Scattered Light

During the preceding report period, interaction amplifier experiments were attempted, and it was noted that scattered light from the high power polarized perturbing beam was overexposing the streak photographs of the polarized beam. It was determined that 17 dB attenuation of the scattered light was required to prevent overexposure. By using a sheet polarizer in the spectrograph, an improvement of only about 5 dB was possible since the light from the polarized perturbing beam suffered depolarization upon scattering. Scattered light from the perturbing beam was finally eliminated by a) placing a 0.030" wide slit at 0.250" in front of the normal slit of the spectrometer, and b) rearranging the angular geometry of the probe and perturbing beams. Useful streak photographs of the probe and perturbing beams could now be taken.

2. Abnormally Low Gain at Liquid Nitrogen Temperature

During the interaction amplifier experiments at cryogenic temperature, it was noted that below a certain temperature the gain of the interaction amplifier rod was sharply reduced. In contrast to this, from data reported[1] on the relative fluorescent intensities at 300^oK and 77^oK which shows a relatively small difference in linewidths, a small increase (10% at most) in gain is expected. In attempting to control better the temperature of the rod, it was noted that the reduction in gain was time dependent, i.e., if the rod temperature was lowered to 77^oK the gain would not decrease until after about 30 minutes. It was discovered that the loss in gain was due to a thin layer of frost on the ends of the interaction amplifier rod. The frost was barely observable at

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(1)American Optical Co., AOLux Neodymium-Doped Glass Laser Rods Specification Sheet 13-5180-A, Fig. 2 (1965)

visible wavelengths, but it caused 50-60% loss at a wavelength of 1.06 microns. The moisture causing the frost came from the laboratory pipe supply of flowing nitrogen which was used to eliminate the atmosphere from the rod ends. This effect of abnormally low gain was eliminated by using dry nitrogen gas from a cylinder.

3.   Change of Gain as a Function of Temperature

After the experimental setup was modified as described above, the net gain of the Interaction Amplifier (IA) rod was measured as a function of rod temperature holding the pump energy constant. The input signal was always less than one joule so the measured gain was nearly the small signal gain. The Q-switched perturbing pulse was recorded before and after the IA by using beam splitters. A typical trace recorded on a Tektronix 519 oscilloscope is shown in Fig. 1 with the output pulses delayed 50 nsec to the right of the input pulses. The peak value of the net small signal gain is calculated from the relative heights of the pulses passing through the IA unpumped, and pumped with 5.4 kilojoules. The change in net small signal peak gain as a function of temperature is actually the combined result of possible changes in pump band absorption as well as 1.06 μ stimulated emission cross section. When Nd-doped glass is cooled to 77°K, the pump band absorption decreases,[2] but as a consequence of the narrowing of the fluorescence linewidth[3] the stimulated emission cross section increases. The result of these two competing effects was an 18% increase in gain (see Fig. 2) when the rod was cooled from 300°K to 77°K. The increase is about 0.06 dB/cm and should not adversely affect the measurements as a function of temperature.

(2)E. Snitzer and C.G. Young, "Glass Lasers" in Lasers, A Series of Advances, Edited by A.K. Levine, New York:Marcel Dekker, Vol. 2, Chap. 2, pp. 200-202 (1968)

(3)American Optical Co., AOLux Neodymium-Doped Glass Laser Rods Specification Sheet 13-5180-A, Fig. 2 (1965)
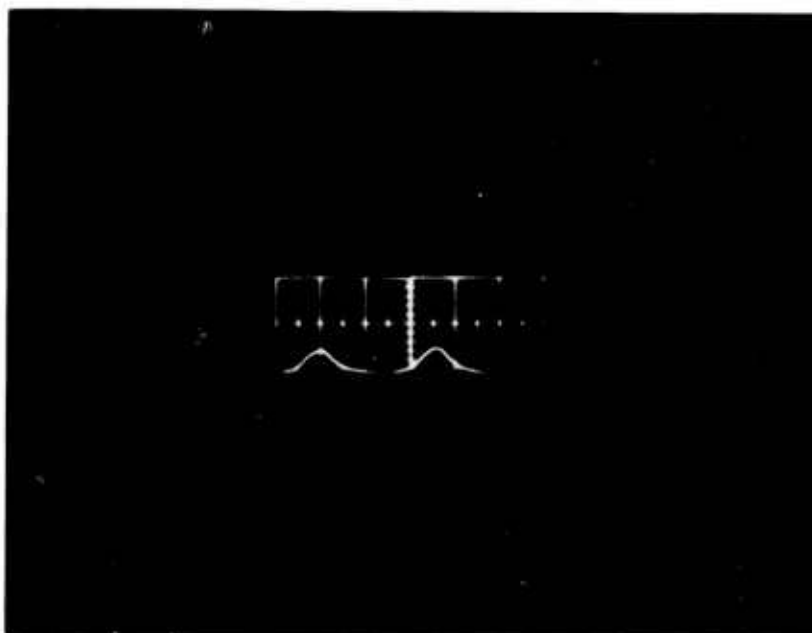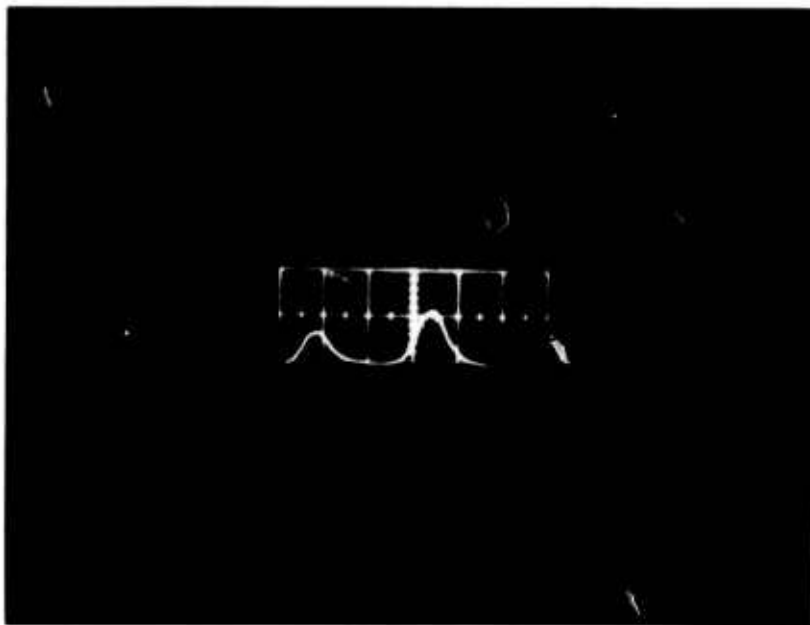
Interaction Amplifier Unpumped

Interaction Amplifier Pumped

Fig. 1 Q-Switched Perturbing Pulse Before and After
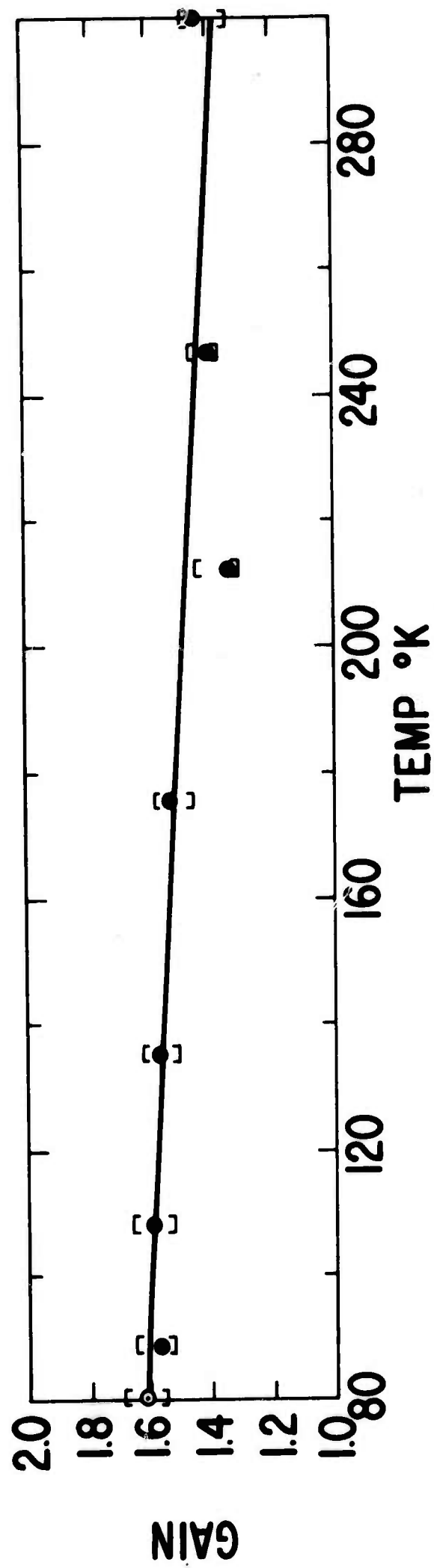Passing Through the Interaction Amplifier

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FIG. 2 INTRACTION AMPLIFIER GAIN AS A FUNCTION OF TEMPERATURE

B. LIFETIME OF THE $^4I_{11/2}$ TERMINAL LEVEL

1. Introduction

Further consideration has been given to the interpretation of the expected results from the interaction amplifier experiment. The initial objective was to measure the time required to transfer energy across the fluorescence linewidth after the active medium in the interaction amplifier is perturbed by an intense beam of short duration. Recent experimental results indicate that the energy transfer rate may be quite rapid and equilibrium is established within perhaps a few nanoseconds. Furthermore, it has been reported[4] that the lifetime of the $^4I_{11/2}$ laser terminal level in Nd-doped glass may be in the order of 25 to 90 nanoseconds. Thus it is evident that the measurements from the interaction amplifier experiment will be influenced by both the energy transfer rate as well as the lifetime of the terminal level. These two effects can be separated if the total width of the perturbing laser spectral output is equal essentially to the fluorescence linewidth, because under this condition no energy transfer occurs.

It appears instructive to discuss a) the qualitative behavior of interaction amplifier experimental measurements based on some assumptions, and b) the techniques used to analyze the results. The first two assumptions are that

a) the effect of the optical pumping can be neglected during the time period under consideration (~100 nanoseconds), and

b) the spontaneous emission losses from the upper laser level can also be neglected within the same period.

It will be further assumed that

a) the Q-switched perturbing pulse has a rectangular shape and its duration τ_Q will be in the order of tens of nanoseconds.

_____

(4)Maurice Michon, "The influence of Nd^{3+} ion properties in a glass matrix on the dynamics of a Q-spoiled laser", IEEE J. Quantum Electronics, vol. QE-2, pp. 612-616, September 1966

Under the limiting cases of the terminal level lifetime τ_1 equal to either zero or infinity, the populations of N_2, N_1, and N_2-N_1 as a function of time are depicted in Fig. 3. From these, the probable size and shape of the pulse after passing through the interaction amplifier are also depicted. The population difference N_2-N_1 becomes zero during the pulse since it is assumed that the pulse is very intense.

If τ_1 is comparable to τ_Q then the probable behavior is depicted in Fig. 3b. From this, it is evident that the effect of a finite value of terminal level lifetime τ_1 is for N_2-N_1, after the perturbing pulse, to increase from zero to a finite value. The time required for N_2-N_1 to reach a prescribed value is a measure of τ_1. This prescribed value will be discussed later. Thus by measuring the post-pulse small signal gain which is related to N_2-N_1, τ_1 can be determined.

By comparing Figs. 3a, b, and c it can be seen that the size and shape of the output pulse is influenced by the terminal level lifetime τ_1. The output pulse is also affected by the magnitude of the input pulse as well as N_2 of the interaction amplifier rod.

The case of a relatively weak perturbing pulse is shown in Fig. 3d, e, and f. The size and shape of the output pulse compared to those of the weak input perturbing pulse are less dramatic than for the case of a very intense perturbing pulse.

2. Post-Pulse Small Signal Gain

As mentioned above, the terminal level lifetime can be determined after passage of an intense perturbing pulse by measuring the increase, or recovery, in the small signal gain. Experimentally this is accomplished by observing the intensities of the lines on the streak photographs. The analytical derivation is given below.

Let us assume that the population of the upper laser level is N_{2B} and the terminal level is $N_{1B} = 0$ before passage of a short-duration perturbing beam
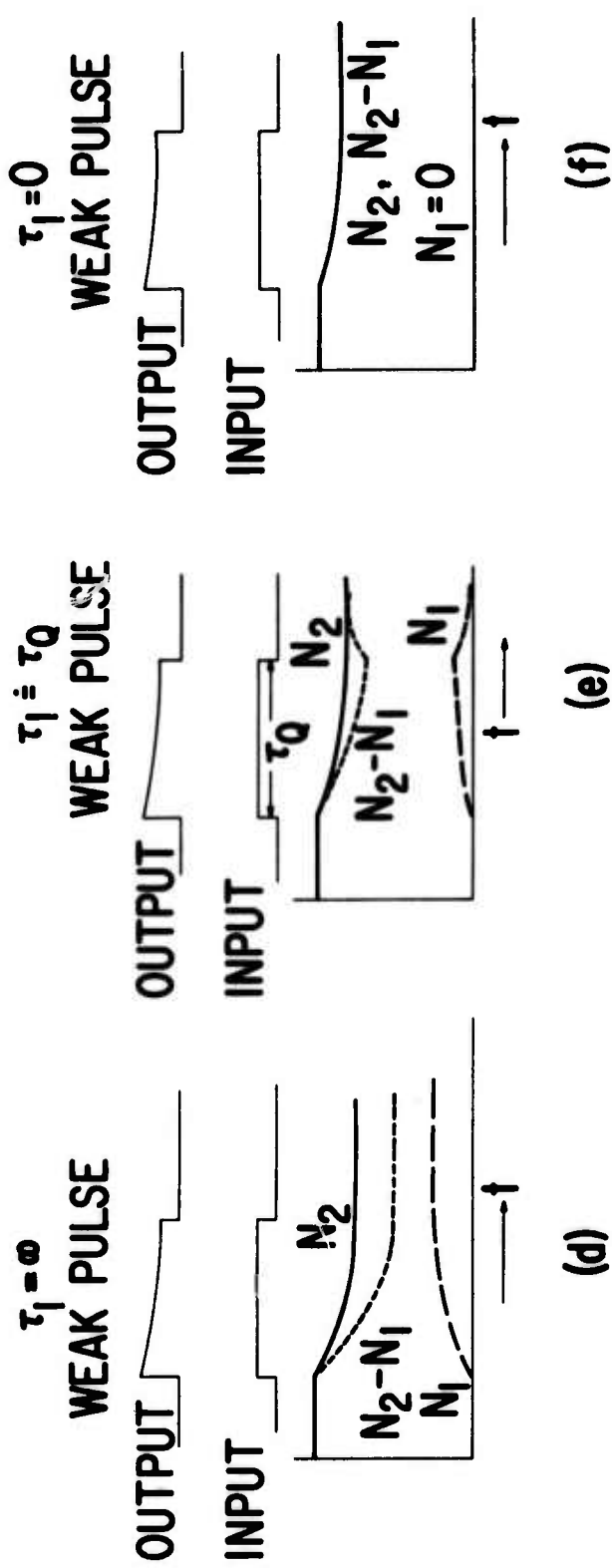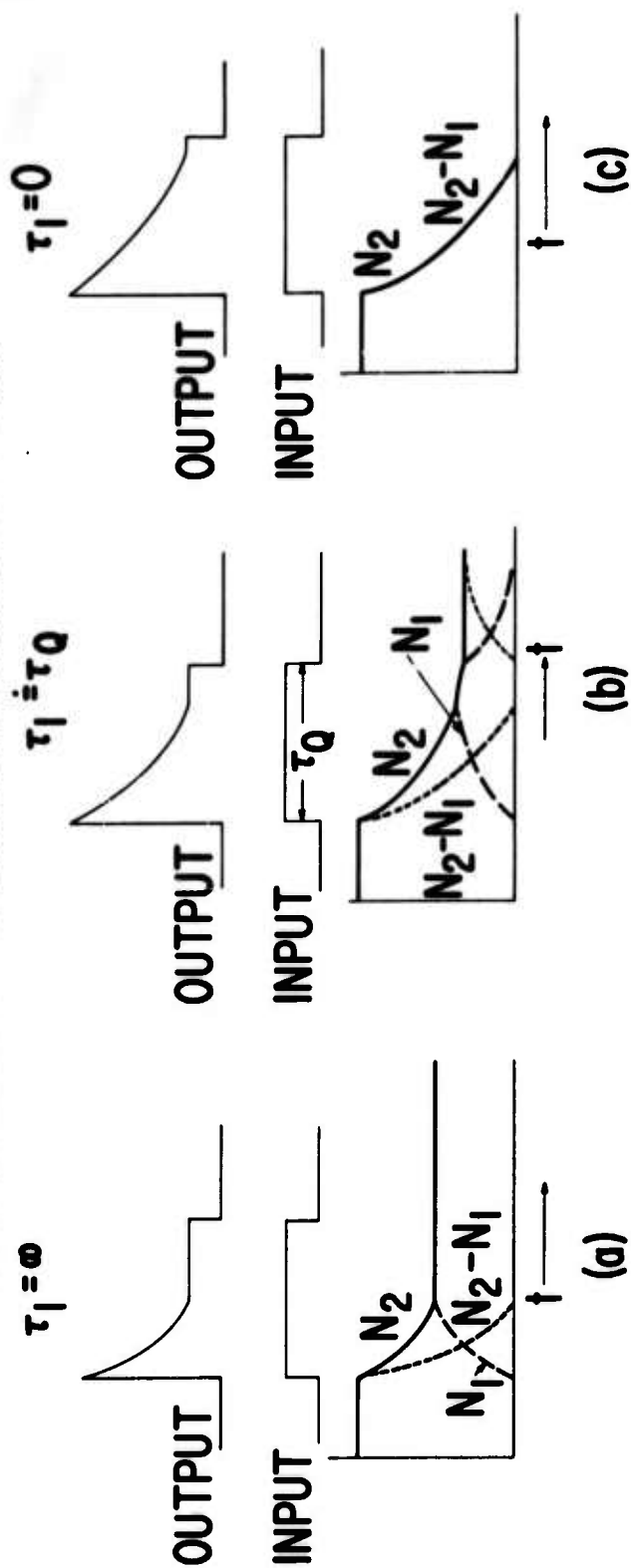
8

FIG. 3   EFFECT OF TERMINAL LEVEL LIFETIME ON
AMPLIFIER RESPONSE

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with sufficient intensity to produce saturation. Immediately after the pulse, arbitrarily set at time t = 0, the upper laser level population $N_{20} = 1/2 \, N_{2B}$ and terminal level population $N_{10} = 1/2 \, N_{2B}$. At this instant $N_{20} - N_{10} = 0$ so that the gain will be zero. Thereafter the terminal level population $N_1(t)$ will relax to the ground level at an exponential rate:

$$N_1(t) = N_{10} e^{-t/\tau_1}$$

where $\quad \tau_1$ = terminal level lifetime.

The small signal gain when t > 0 will be dictated by the quantity $N_{20} - N_1(t)$ so that at a time t long compared to τ_1, the gain will recover to one-half of the pre-pulse value assuming fluorescence losses and optical pumping effects can be neglected. If the perturbing pulse intensity is inadequate to saturate the entire length of the amplifier, the post-pulse gain will not fall down to zero, and the recovery will be a smaller absolute change in gain.

If the perturbing pulse duration is much longer than τ_1, the terminal level population N_{10} will not have an appreciable magnitude. However, it is more likely that τ_1 will be on the order of the perturbing pulse duration, so the gain after terminal level relaxation will not recover up to one-half of the pre-pulse value.

For the case of a short duration perturbing pulse with arbitrary intensity, the populations of the upper and terminal levels, at the instant t = 0 when the end of the pulse passes the exit face of the amplifier rod, are $N_{20}(z)$ and $N_{10}(z)$ respectively. Thus the gain g(z,t) per unit length for t > 0 is

$$g(z,t) = q \left[N_{20}(z) - N_{10}(z) e^{-t/\tau_1} \right]$$

where $\quad$ q = proportionality constant.

Thus the total small signal gain $G_N(t)$ through the amplifier rod of length L is

$$G_N(t) = \exp \left[\int_0^L g(z,t) dz \right]$$

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$$= \exp \left[q \int_0^L N_{20}(z)dz - q \int_0^L N_{10}(z)e^{-t/\tau_1}dz \right]$$

If we define the time-independent factors

$$B = \exp \left[q \int_0^L N_{20}(z)dz \right]$$

$$C = q \int_0^L N_{10}(z)dz$$

then the total gain is

$$G_N(t) = B \exp \left[-Ce^{-t/\tau_1} \right].$$

If the logarithm is taken of both sides, then

$$\ln G_N(t) = \ln B - Ce^{-t/\tau_1}.$$

This if the post-pulse total gain $G_N(t)$ is plotted on a log scale as a function of time, τ_1 can be determined from the time required for $\ln G_N$ to reach the fractional value of e^{-1} of the eventual change C. This determination is independent of the intensity of the perturbing pulse; however, if the intensity is small, C will be small and thus the measurement will be more difficult to make.

3. Theoretical Gain Response of a Laser Amplifier

A second method of determining the terminal level lifetime involves measurement of the output pulse relative to the input pulse. As discussed qualitatively the effect of a terminal level lifetime τ_1 that is either long or comparable to the length τ_Q of the perturbing pulse is to prevent extraction of the entire stored energy represented by the upper level population N_2. In order to analyze the amplification process in the presence of a finite value of τ_1, it is instructive to start with the usual rate equations for a 4-level laser amplifier.[5] The levels involved are designated in the following diagram:

(5)Amnon Yariv, Quantum Electronics, New York:John Wiley & Sons, Chapter 15 (1967)

Level
Designations

3 //////// pump bands

2 ———————— upper metastable level

1 ———————— terminal level

0 ———————— ground level
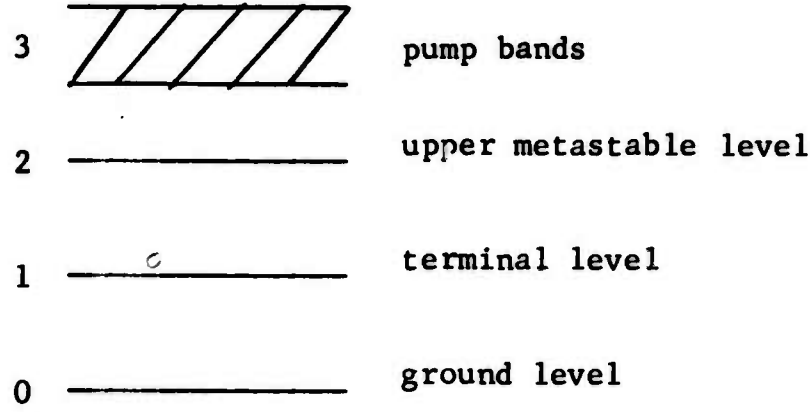
$$\frac{dN_2}{dt} = -N_2\omega_{21} - W(N_2-N_1) + R_{32} + R_{02} \tag{1}$$

$$\frac{dN_1}{dt} = N_2\omega_{21} + W(N_2-N_1) + R_{01} - RN_1 \tag{2}$$

where ω_{ij} = relaxation rate between i and j levels

   W = induced transition rate at laser wavelength

   R_{ij} = pumping rate from i to j level

   R = relaxation rate of terminal level

Within the order of magnitude of the terminal level lifetime, which is tens of nanoseconds, the optical pumping effects and the relaxation loss from level 2 can be considered negligible relative to the other processes. Thus the rate equations can be simplified:

$$\frac{dN_2}{dt} = -W(N_2-N_1) \tag{3}$$

$$\frac{dN_1}{dt} = W(N_2-N_1) - RN_1 \tag{4}$$

If (4) is subtracted from (3),

$$\frac{d(N_2-N_1)}{dt} = -2W(N_2-N_1) + RN_1 \tag{5}$$

Equation (5) can be written alternatively as

$$\frac{d(N_2-N_1)}{dt} = -2W(N_2-N_1) - R(N_2-N_1) + RN_2 \tag{6}$$

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Since the gain g per unit length is proportional to $N_2 - N_1$, (6) can be rewritten as

$$\frac{dg}{dt} = -2Wg - Rg + RN_2 q \tag{7}$$

where   q = proportionality constant

By differentiating (7) and using (3) for dN_2/dt, the following is obtained:

$$\frac{d^2 g}{dt^2} = -2W\frac{dg}{dt} - 2g\frac{dW}{dt} - R\frac{dg}{dt} - RWg \tag{8}$$

The differential equation for a pulse in a traveling wave amplifier has been given[6] and is rewritten in the present notation:

$$\frac{\partial W}{\partial t} + c\frac{\partial W}{\partial z} = cWg \tag{9}$$

The characteristic of a propagating pulse is given by (8) and (9).

These nonlinear coupled differential equations are functions of time and position along the amplifier. The exact solution to these equations are difficult to obtain using even a computer. However by considering small but finite increments of time and length, an approximate and meaningful solution can be obtained. The increment of length is chosen small enough so that an average gain can be specified with sufficient accuracy. The increment of time has to be chosen short enough so that

a)   an average power can be specified with sufficient accuracy,

b)   the total energy within the increment (at maximum power) is much less than that required for saturation, and

c)   it will be much less than the terminal level lifetime τ_1.

In order to carry out the analysis, the following terms with regard to the subdivision of the pulse and amplifier rod will be defined below and are illustrated in Fig. 4:

---

[6] Lee M. Frantz and John S. Nodvik, "Theory of pulse propagation in a laser amplifier", J. Appl. Phys., vol. 34, pp. 2346-2349, August 1963
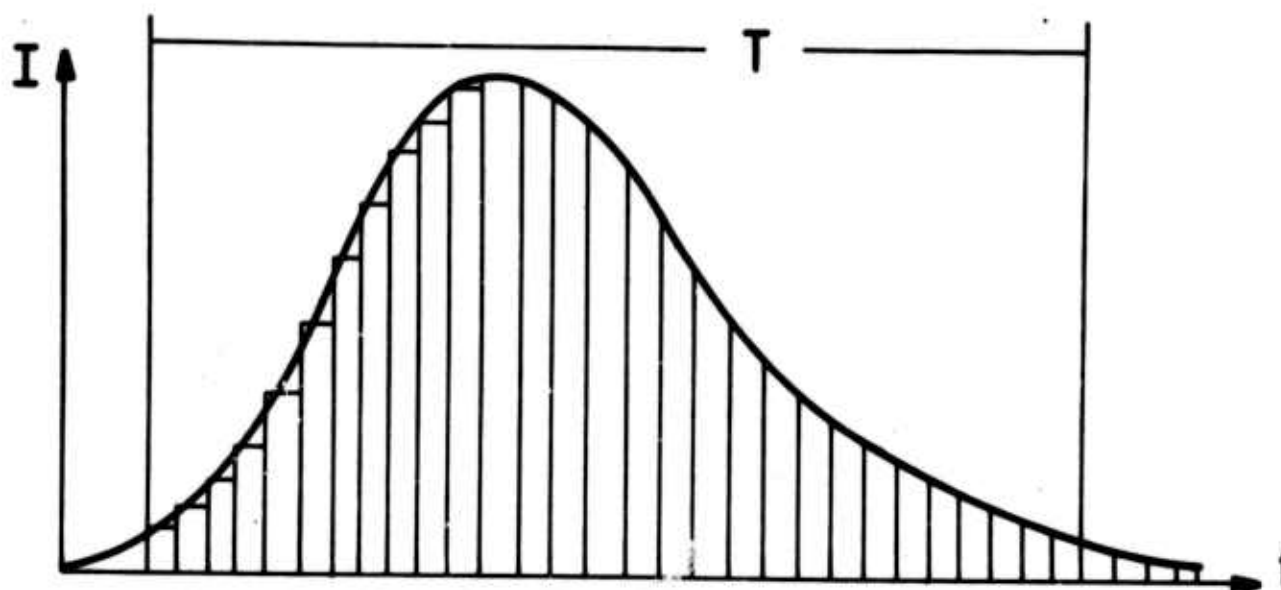
T = LENGTH OF PULSE AT 10% HEIGHT
m = NO. OF TIME INCREMENTS
$\Delta t = T \div m$ = DURATION OF TIME INCREMENT
j = INTEGER, $0 \leq j \leq m$

W_{jk} = AMPLITUDE MATRIX OF TIME
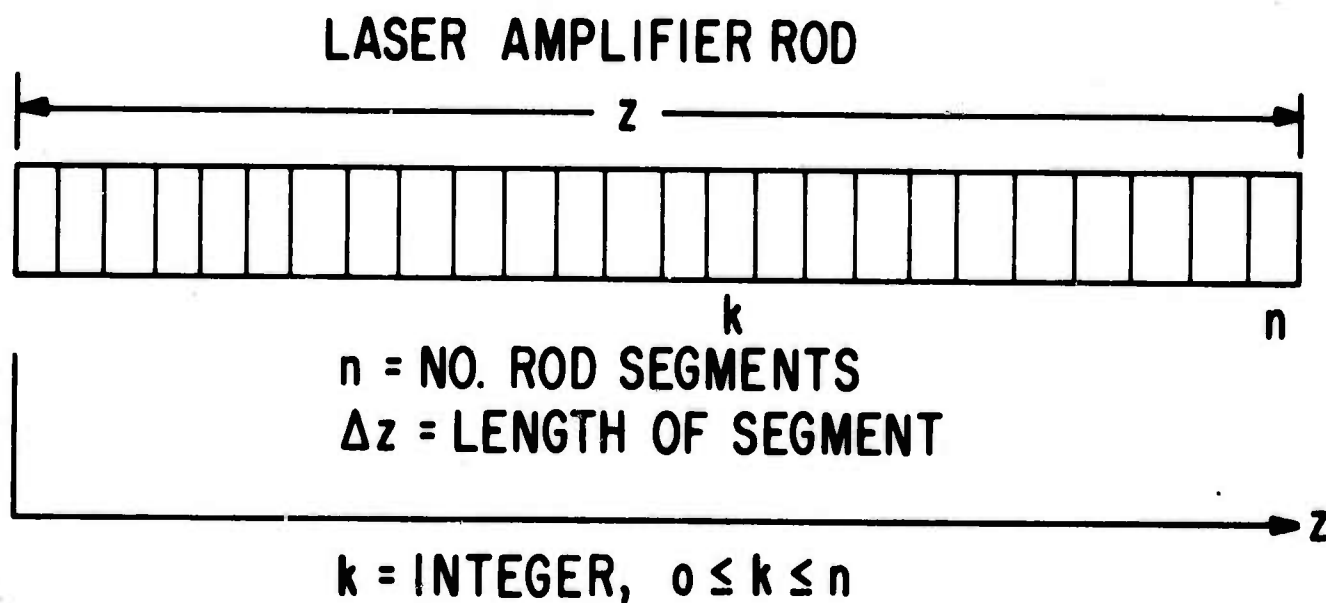INCREMENT j AND ITS VALUE
AFTER PASSING THROUGH
AMPLIFIER SEGMENT k

LASER AMPLIFIER ROD

n = NO. ROD SEGMENTS
Δz = LENGTH OF SEGMENT

k = INTEGER, $0 \leq k \leq n$

FIG. 4 SUBDIVISION OF PULSE AND AMPLIFIER
ROD

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t = time variable

T = total pulse length

Δt = increment of time

j = particular time increment within pulse length

$m = \dfrac{T}{\Delta t}$ = total number of time increments during pulse

z = length variable

Z = total amplifier length

Δz = increment of length

k = particular length increment or segment (longitudinal position) within amplifier

$n = \dfrac{Z}{\Delta z}$ = total number of segments in amplifier

The change in population due to a propagating pulse of increment Δt at $t = j$ in any segment $z = k$ can be obtained from (3) and is rewritten as

$$-\Delta N_2(j,k) = \Delta N_1(j,k) = g(j-1,k)\, \frac{1}{q}\, W(j-1,k)\, \Delta t \qquad (10)$$

where $j-1$ = time increment preceding j

W = induced transition rate at laser wavelength

The gain per unit length $g(j,k)$ in segment k is proportional to the population difference $N_2(j,k) - N_1(j,k)$ so that $g(j,k)$ is a function of history from $t = 0$ to $t = j$. As the pulse progresses in time, N_2 will decrease and N_1 will increase. However, as the terminal level population N_1 builds up, it will decay or relax to ground state with a lifetime of τ_1. Thus

$$g(j,k) = q\left\{ N_2(0,k) - \sum_{t=1}^{t=j} \Delta N_1(j,k)\left[1 + e^{-(j-t)\Delta t/\tau_1}\right]\right\} \qquad (11)$$

where $N_2(0,k)$ = population in segment k at $t = 0$.

Note that for $t = j = 1$, the gain in segment k is

$$g(1,k) = q[N_2(0,k) - 2\Delta N_1(1,k)]$$

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The induced transition rate $W(j,k)$ at the laser wavelength is related to the laser beam intensity, and the value of $W(j,k)$ after experiencing gain from a segment k of the amplifier at time $t = j$ is related to $W(j,k-1)$. $W(j,k)$ can be obtained from (9) by letting $\partial W/\partial t = 0$. Thus,

$$W(j,k) = W(j,k-1) \; e^{g(j,k-1)\Delta z} \tag{12}$$

The present incremental analysis employing a computer requires the sequential solution of (10), (11), and (12) for each value of $t = j$ by starting from $k = 1$ to $k = n$. This method of computation assumes that the pulse transit time τ_z through the rod

$$\tau_z = \frac{z}{\eta c}$$

where η = index of refraction

c = velocity of light

is short compared to the terminal level lifetime τ_1, i.e., $\tau_z \ll \tau_1$.

For an assumed distribution of $N_2(0,z)$, an arbitrary input pulse of $W(t,1)$ and an assumed value of terminal level lifetime τ_1, a $(m) \times (n)$ array of quantities for each of $g(j,k)$ $W(j,k)$, $N_2(j,k)$ will be obtained. By varying τ_1 different arrays of quantities can be calculated.

By assuming the short transit time through the amplifier, the output W_{jz} for time increment j can be calculated and it is related to the input W_{j1} by the following:

$$W_{jz} = W_{j1} \; e^{g_{j1}\Delta z} \; e^{g_{j2}\Delta z} \; e^{g_{j3}\Delta z} \; \ldots \ldots \tag{13}$$

After taking the logarithm, (13) becomes

$$\ln W_{jz} = \ln W_{j1} + \sum_1^z g_{jk}\Delta z \tag{14}$$

The overall gain $G(j) = \dfrac{W_{jz}}{W_{j1}}$ so that (14) can be rewritten as

$$\ln G(j) = \sum_1^z g_{jk}\Delta z \tag{15}$$

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This is the overall gain at the increment of time j. The overall gain as a function of time is obtained by letting j range from 1 to T, and this can be displayed by the following set of equations:

$$
\begin{bmatrix}
\ln G_1 \\
\ln G_2 \\
\cdot \\
\ln G_j \\
\cdot \\
\ln G_T
\end{bmatrix}
= \Delta z
\begin{bmatrix}
g_{11} & g_{12} & \cdots & g_{1k} & g_{1Z} \\
g_{21} & \cdots & \cdots & \cdots & \cdots \\
\cdot & \cdot & & & \\
g_{j1} & \cdots & \cdots & \cdots & \cdots \\
\cdot & \cdot & & & \\
g_{T1} & \cdots & \cdots & \cdots & \cdots
\end{bmatrix}
\begin{bmatrix}
1 \\
1 \\
\cdot \\
1 \\
\cdot \\
1
\end{bmatrix}
$$

This set of equations can be conveniently presented by the following matrix equation:

$$[\ln G_j] = \Delta z \, [g_{jk}][1]$$

Although the foregoing analysis was directed toward the amplifier response during the perturbing pulse, it can be extended very readily to the post-pulse period by letting the input pulse $W_{t1} = 0$ for a time equal to $3\tau_Q$. A probe signal can be used to explore the post-pulse gain response.

The analytical method will be to calculate the time-dependent gain response of the amplifier during and after the perturbing pulse as a function of the terminal level lifetime τ_1, and the value of τ_1 will be determined by comparing (or curve fitting) the theoretical responses with the experimental measurements.

4. Parameters Influencing Terminal Level Lifetime

In order to determine the mechanisms which influence the $^4I_{11/2}$ terminal level lifetime, a set of experiments will be carried out measuring the lifetime as a function of temperature and concentration of Nd ions in one type of glass host.

In certain lattices, the portion of the relaxation time that varies with temperature is caused by coupling to acoustic phonons. The form of temperature

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variance for phonon coupling is well-known[7] and this term should be distinguishable as a function of temperature. It is expected that Nd-doped glass hosts will behave in a similar manner.

The relaxation mechanisms which are affected by strains in the host, and hence vary from Nd site to site, are temperature independent. When the temperature is lowered it should be possible to separate out a residual component of the lifetime which doesn't vary with temperature.[8,9] The magnitude of this component is important in relation to other mechanisms because it would affect the assumption made earlier in that the relaxation process to the ground state behaves as a single exponential.

If the measurement of lifetime as a function of concentration yields a parameter dependence, this would be related to ion-ion coupling. This variance with ion separation shall be used to determine the prominent coupling forces between Nd ions in a glass host.

5. Preliminary Measurements of Terminal Level Lifetime at Room Temperature

Preliminary measurements of the lifetime of the $^4I_{11/2}$ terminal level have been made at room temperature on American Optical 1838 light barium crown 2% Nd-doped glass. The measurements were made using the interaction amplifier experimental setup with a broadband (100 Å) 5-joule Q-switched perturbing laser beam. Streak photographs were taken of the spectral output from the normal pulsed probe laser passing through the interaction amplifier. A densitometer was employed to transform film exposure to spectral amplitude. The amplitude

(7)T.A. Bak, Phonons and Phonon Interactions, New York:W.A. Benjamin, Inc. (1964)

(8)A.L. Schawlow, "Fine structure and properties of chromium fluorescence in aluminum and magnesium oxide", Advances in Quantum Electronics, Edited by Jay R. Singer, New York:Columbia U. Press, pp. 51-64 (1961)

(9)A.L. Schawlow, "Widths and positions of sharp optical lines in solids", Proc. Third International Congress on Quantum Electronics, Edited by P. Grivet and N. Bloembergen, New York:Columbia U. Press, pp. 645-653 (1964)

was plotted as a function of time and this is shown in Fig. 5. The plot
resembles that shown in Fig. 3b, but since the perturbing pulse energy was
below saturation, the recovery in gain was not as pronounced. The data in
Fig. 5 was replotted on semi-log graph paper (see Fig. 6) as discussed in
Part B. 2 in order to determine the terminal level lifetime. The resultant
value of the lifetime is estimated to fall between 20 and 50 nanoseconds. A
more accurate value could not be determined because the finite fall time of
the perturbing pulse makes it impossible to establish the time $t = 0$ required
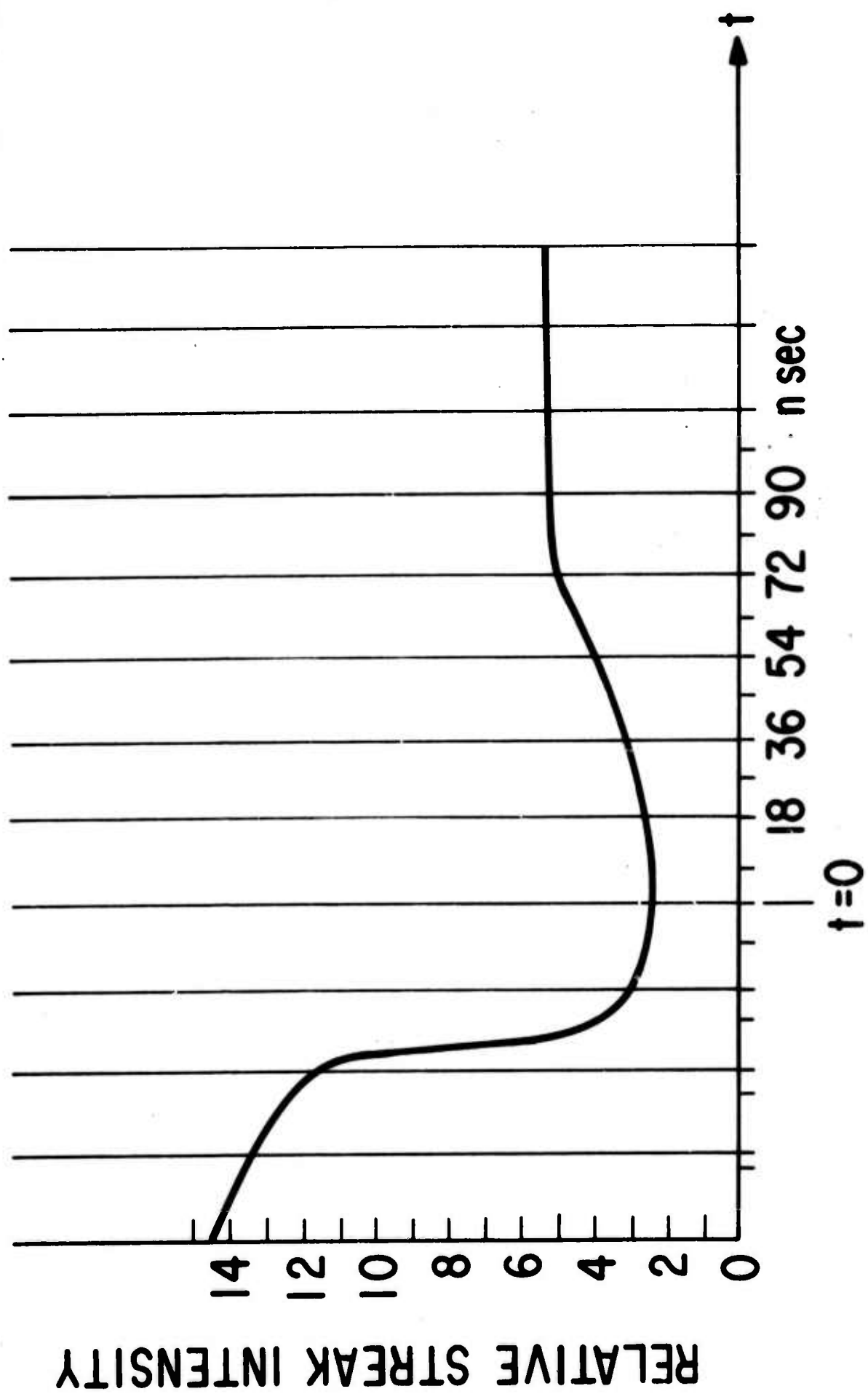for the plot in Fig. 6 without processing the data on a computer.
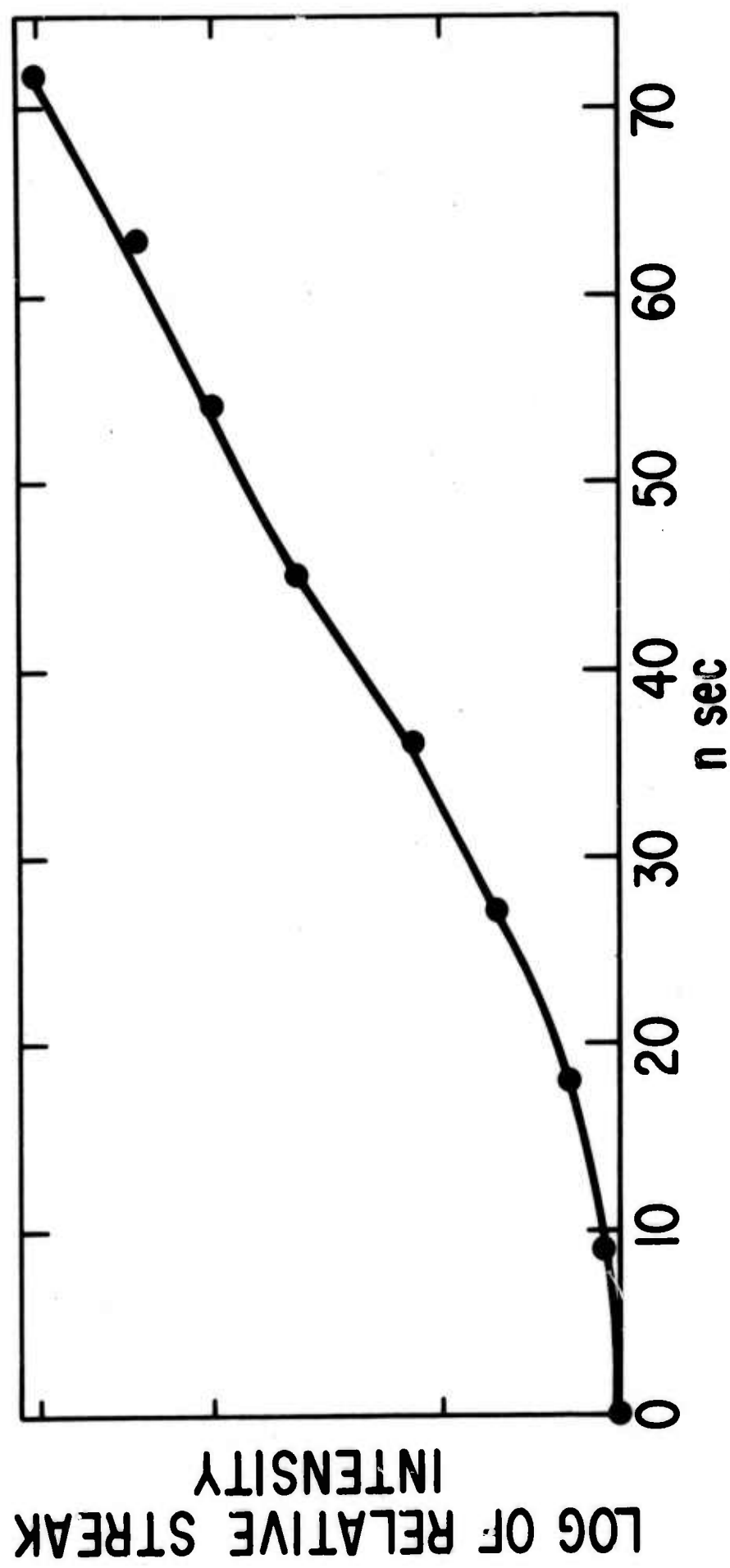
FIG. 5 AMPLITUDE OF ONE STREAK

FIG. 6   SEMILOG PLOT OF GAIN RECOVERY

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13. ABSTRACT

This is a semi-annual report on investigations of cross relaxation between
neodymium ions and measurements of $^4I_{11/2}$ lifetime in laser glass. Work performed
during the last six months is described.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Neodymium Glass Laser						
Interaction Study						
Energy Transfer						
Rare Earth Ions						
Cross Relaxation						
$^4I_{11/2}$ Lifetime						